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Uncertainties in radiance calibrations of backscatter ultraviolet (BUV) instruments

S. Janz, E. Hilsenrath, J. Butler, D. F. Heath and R. P. Cebula

Abstract. Traditional radiance calibrations of solar backscatter ultraviolet (SBUV) instruments require a measurement of the bidirectional-reflectance distribution function (BRDF) of a flat-plate diffuser. To date the BRDF of the diffusers used for calibrating the Shuttle-borne SBUV instrument (SSBUV), has relied on an initial measurement of a sample plate coated with $BaSO_4$ made by the National Institutes of Standards and Technology (NIST). Changes in the reflectance of the calibration diffusers were tracked over time with measurements of their total hemispherical reflectance. Preliminary comparisons of direct measurements of the BRDF using a new facility at the NASA/Goddard Space Flight Center, inferred BRDF values using an integrating sphere, and the NIST-based values, show significant inconsistencies. In general, direct measurements of BRDF values compare to within 1 % of those inferred from integrating sphere measurements. However, these values differ from the NIST-based values by about 6 %. These differences and their uncertainties are discussed. The results imply that SSBUV-measured vertical ozone profile values have an altitude-dependent error of between 3 % and –12 %, but there should be little effect on the measured total ozone values.

1. Introduction

Since the comparison of BUV radiation with the solar radiation incident on the Earth's atmosphere was first proposed in the late 1950s [1], it has become a well-established means of measuring both the total column ozone amount and the vertical ozone profiles in the stratosphere. The current generation of SBUV and TOMS (Total Ozone Mapping Spectrometer) instruments has been flown on satellites and on the Space Shuttle, beginning with Nimbus-4 [2] in the early 1970s and Nimbus-7, which was launched in 1978. Currently, there are functional SBUV-2 instruments on NOAA-9 and NOAA-14. The Space Shuttle instrument, SSBUV, has flown about once a year beginning in 1989. Planned flights exist for a series of NOAA instruments to continue into the next decade. Three more TOMS instruments are scheduled to be launched in the latter half of the 1990s.

Both the SBUV and TOMS instruments employ two viewing modes, one for viewing Earth radiance and the other for viewing solar irradiance. The solar view employs either a reflective diffuser or, in the case of the SSBUV instrument, a transmission diffuser. The ratio of the terrestrial-scene radiance to solar irradiance is termed the geometrical albedo. SBUV instruments measure the Earth albedo at twelve discrete wavelengths from 250 nm to 340 nm in the Hartley and Huggins bands, while TOMS instruments make measurements at six wavelengths from 300 nm to 380 nm. Calibration of both these viewing modes is necessary to retrieve ozone data.

As more data sets from these instruments need to be examined for long-term ozone trends, the accuracy of absolute ground-based calibrations becomes increasingly important. The primary uncertainty in traditional albedo calibrations is the BRDF of the targets used as radiance sources, and this paper addresses this uncertainty as detected by the SSBUV instrument. The SSBUV instrument is part of a US national plan for monitoring long-term, global ozone depletion [3]. The cross-calibration technique between the Shuttle instrument and satellite instruments is presented by Frederick et al. [4], and calibration results and stability by Cebula et al. [5] and Hilsenrath et al. [6, 7].

2. Calibration techniques

Ground-based calibration of SBUV instruments in the irradiance mode is achieved using NIST spectral-irradiance standards which illuminate the instrument diffuser. The scale uncertainties in these standards are

S. Janz: IDEA Incorporated, Beltsville, MD 20705, USA.
E. Hilsenrath and J. Butler: NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA.
D. F. Heath: Research and Support Instruments, Boulder, CO 80301, USA.
R. P. Cebula: Hughes STX Corporation, Greenbelt, MD 20770, USA.

typically less than 2 % at the 3σ level [8], and to first order they cancel out in the albedo calibration. The equation describing the instrument sensitivity in the irradiance mode is

$$K_\lambda = \frac{E_\lambda \cdot G(\theta,\ \phi)}{C_\lambda}, \tag{1}$$

where E_λ is the source irradiance, $G(\theta,\ \phi)$ is a goniometric factor, and C_λ is the instrument response in counts on one of three gain ranges. Traditional radiance calibrations have relied on diffuse targets of $BaSO_4$ as radiance sources. The equivalent calibration constant for the radiance mode, assuming normal illumination of the target, is

$$k_\lambda = \frac{E_\lambda \cdot B(\lambda,\ \theta) \cdot F(\theta,\ \phi)}{c_\lambda} = \frac{L_\lambda}{c_\lambda}, \tag{2}$$

where $F(\theta,\ \phi)$ is a correction factor for instrument vignetting and off-axis illumination of the viewing target, $B(\lambda,\ \theta)$ is the bidirectional-reflectance distribution function (BRDF) of the illuminated target, and c_λ is the response of the instrument in counts. The numerator in (2) is the target radiance L_λ. The albedo calibration is just the ratio of (2) to (1) and it can be seen that the source irradiance cancels.

For the SSBUV instrument, the initial BRDF measurements were performed at the NIST on sample plates coated with the same $BaSO_4$ paint as were the 30,5 cm × 30,5 cm plates used for radiance calibrations. BRDF measurements were made for a normally incident source at viewing angles ranging from 24° to 36° to cover the SSBUV instrument's 11,5° field-of-view. The NIST facility was not capable of making BRDF measurements on the calibration plates due to their size, so it was decided to track in the plates long-term changes using periodic measurements of *R*, the 6° total hemispherical reflectance (THR). The NIST facility and test setup for the THR measurement is described by Weidner and Hsia [9]. The THR of a material is the ratio of the radiation reflected off the material, collected over the full hemisphere, to the same quantity using a perfectly reflecting diffuser. The angle of incidence for the measurements was 6° which allows the specular component to be included in the THR. This indicates that the assumption made in using THR changes to infer BRDF changes is one of uniformity in angular degradation. Figure 1 shows THR changes observed in the calibration diffuser plates over several years, as measured by the NIST.

These measurements show decreases in THR of about 3 %/year at 250 nm and 1,2 %/year at 340 nm. The BRDF values derived in this way are subject to two uncertainties. First, how well do the original NIST measurements of the BRDF of the sample plates reflect the original BRDF of the calibration plates? Second, how well do the THR measurements track the plate BRDF changes? To address these questions we have begun comparisons using independent measurements

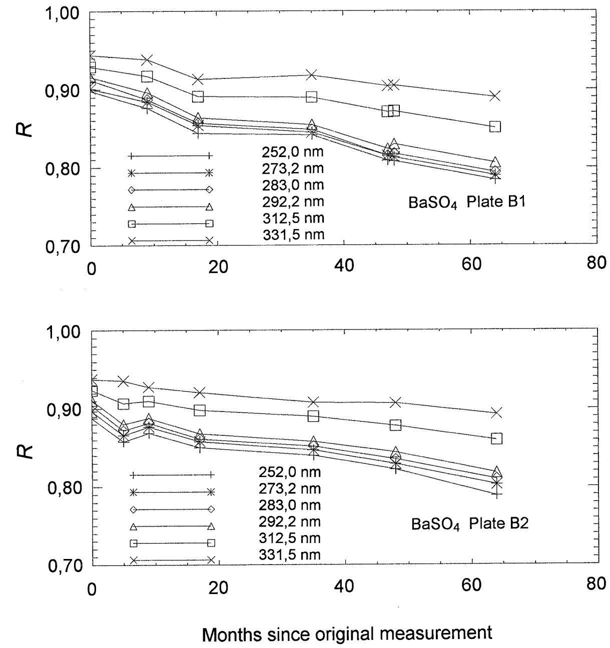

Figure 1. NIST-measured values of *R*, the total hemispherical reflectance (THR), of two $BaSO_4$ diffuser plates over more than five years. The decreases in THR range from 1,2 %/year to 3 %/year.

of the diffuser BRDF made by a new facility at the NASA/Goddard Space Flight Center (GSFC), and the BRDF inferred from calibrations using a large-aperture integrating sphere [10, 11].

The BRDF measurements presented in this paper were carried out with the NASA/GSFC scatterometer. The details of the setup are presented by Schiff et al. [12]. This instrument is capable of making absolute or relative measurements, both in plane and out of plane, of the BRDF and the BTDF (bidirectional-transmission distribution function). The goniometer subsystem is capable of positioning both the source and detector in the desired polar altitude angle and azimuth angle. The wavelength range covered is 230 nm to 900 nm using a broadband xenon arc with wavelength selection via a Czerny-Turner monochromator.

An alternative calibration technique for large-aperture instruments, used extensively for infrared radiometers in space, is that of internally illuminated integrating spheres [13]. Figure 2 shows the calibration setup using an integrating sphere, coated with $BaSO_4$ and internally illuminated by four tungsten halogen lamps. The average sphere port radiance is derived by cross-calibration of the port irradiance to a standard tungsten lamp (FEL) by viewing the FEL and then the sphere through the instrument diffuser. The sphere irradiance is then used to calculate the radiance using the equation

$$E_\lambda = \int_\Omega L_\lambda \, \mathrm{d}\Omega, \tag{3}$$

where E_λ is the spectral irradiance at the instrument due to the radiance at any point of the sphere port, and

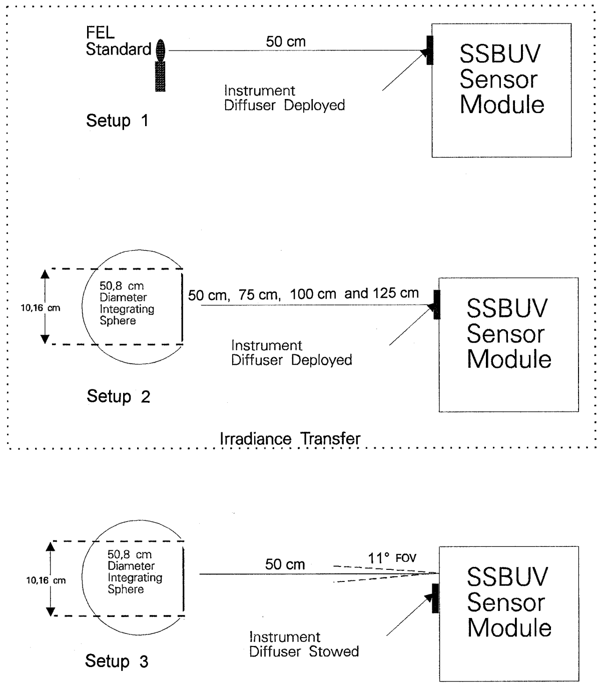

Figure 2. Sphere calibration setup. The upper two panels show the configuration used for irradiance transfer from the FEL lamp to the sphere. The lower panel shows the radiance calibration configuration of the instrument.

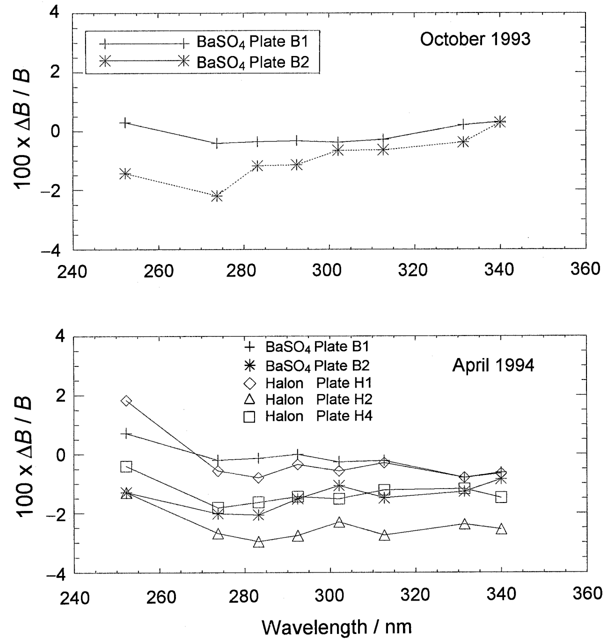

Figure 3. Comparison of the BRDF (B) values as measured by the NASA/GSFC scatterometer and inferred using sphere calibrations. The upper panel shows a comparison using two $BaSO_4$ plates in October 1993 and the lower panel shows the same two plates along with three Halon plates in April 1994. The plotted values $100 \times \Delta B/B$ are

$$\frac{B\,(\mathrm{GSFC}) - B\,(\text{sphere-based})}{B\,(\text{sphere-based})} \times 100.$$

Ω is the solid angle as viewed by the instrument [10]. In the case of circular apertures, and if the radiance is constant over the source aperture, (3) can be reduced to the expression

$$E_\lambda = \frac{\pi r_1^2}{d^2 + r_1^2 + r_2^2} L_\lambda, \tag{4}$$

where r_1 is the source-aperture radius, r_2 is the receiving-aperture radius, and d is the source/receiver separation [10]. The sphere was determined by the NIST to be uniform to 1 % out to the port edges. For SSBUV calibrations, r_1 was 10,16 cm, r_2 was 1,86 cm, and d was varied between 50 cm and 125 cm. The different values of d allow the scaling in (4) to be checked. The goniometric response of the instrument diffuser must also be accounted for as this modifies the irradiance viewed across the sphere port. We define an effective irradiance E'_λ which is the area-weighted average irradiance convolved with the goniometric response of the diffuser. The diffuser response was measured for both instrument axes over the range of angles that the sphere port covers (zero to 6°). Assuming azimuthal symmetry, the corrections to the irradiance derived in this way ranged from about 5 % at $d = 50$ cm to 1,8 % at $d = 100$ cm. The sphere-based results in this paper use the 100 cm derived radiances from (4) with $E_\lambda = E'_\lambda \cdot 1,018$.

3. Comparisons

We compared the results of the GSFC BRDF measurements to the sphere-inferred values by calculating the instrument radiance sensitivity using the sphere and then the average plate BRDF using (2). For all sphere calibrations the scaling of irradiance with d in (4) was found to be within 1 %. The results for two sets of sphere calibrations and concurrent BRDF measurements are given in Figure 3. The scatterometer measurements generally yield values of BRDF lower by 1 % to 2 %. Some of the variation may be related to the fact that the GSFC measurements are made on the plate centre spot whereas the sphere values yield an average over the viewed surface. Future work will include a raster scan of the viewed portion of the target plate to determine BRDF uniformity.

We have also investigated the agreement between the original NIST BRDF, which is degraded by the changes in THR mentioned above, and the sphere values. It should be noted that if a theoretical value is used for the BRDF based on THR for a Lambertian reflector, the original NIST BRDF values are approximately 10 % higher than THR/π. Figure 4 shows the agreement between sphere values and NIST-based values for two different dates on which the THR was measured within 1 month of the sphere calibration. Both measurements indicate about 6 % lower BRDF using the sphere method, with very little wavelength dependency. It appears that the THR tracking is reasonable for the two comparison dates, which spanned about 18 months and a decrease in THR of 1 % to

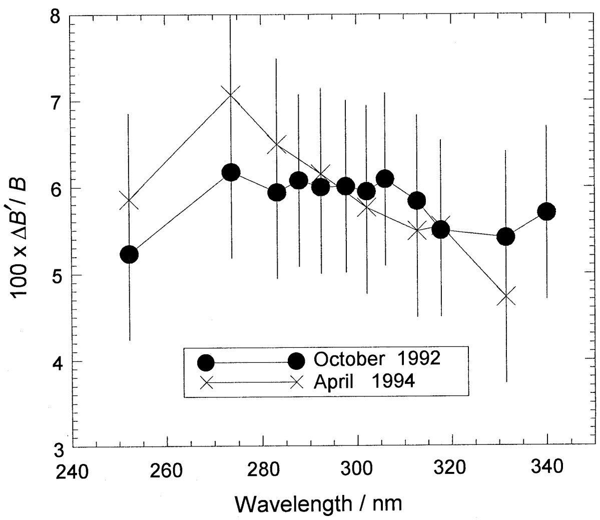

Figure 4. Comparison of NIST-based BRDF (B) and THR (R) measurements to sphere-inferred BRDF values. Original NIST measurements of the BRDF of a sample plate were corrected for UV exposure-induced degradation using NIST-measured THR values. The difference ratios in per cent of instrument calibration constants are plotted using averages of NIST-based measurements of plates B1 and B2 to the sphere-based calibration constant, where

$$100 \times \Delta B'/B = \frac{B\,(\mathrm{NIST}) \times \Delta R - B\,(\text{sphere-based})}{B\,(\text{sphere-based})} \times 100.$$

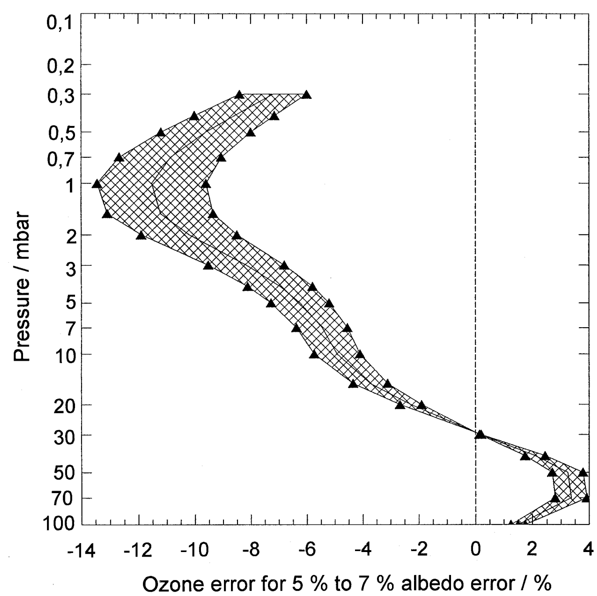

Figure 5. Implication for SSBUV profile measurements of ozone given a wavelength-independent albedo calibration error. The cross-hatched areas represent the range in ozone measurement offsets given a 5 % to 7 % range in BRDF offsets as shown in Figure 4.

3 %. Additional work is needed to determine if the BRDF to THR relationship remains proportional, as this has implications for extrapolation of any corrections to predate the first sphere calibration in October 1992.

4. Implications and conclusions

The implications for ozone measurements performed by the SSBUV instrument with this type of offset in the BRDF values are represented in Figure 5. A BRDF value which is too high generates artificially high backscattered radiances, which in turn imply lower ozone values.

Since the wavelength dependency is small, the albedo error has little effect on the total ozone values because pairs of wavelengths are used for this calculation. However, as shown in Figure 5, the profiles can be dramatically changed, with as much as –12 % error in the calculated ozone amounts at 1 mbar. It should be noted that the total ozone is held fixed in the algorithm, hence the positive errors at higher pressures and negative errors at lower pressures. If there is an additional small variation in total ozone this could have a significant effect on the lower pressure portion of the profile. Further work is needed to determine the validity of small wavelength-dependent changes in the BRDF offsets. Also needed is further validation of the GSFC facility for BRDF measurements. The NIST is currently in the process of upgrading its BRDF measurement facility, which will provide more opportunities for intercomparison. This type of intercomparison will remain crucial to large-area UV radiance calibrations until a radiance standard becomes available.

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